Martian magmatic plumbing and the spacing between Tharsis Montes shield volcanoes

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Major Martian shield volcanoes are similar in size and shape to their Terrestrial counterparts when scaled by gravity, and it has been hypothesized that they also are products of mantle plume-related decompression melting [1]. Despite the absence of plate tectonics to provide a stress guide, some Martian shield volcanoes, in particular the Tharsis Montes chain, have strong alignment and quasi-regular spacing. This is suggestive of structural or dynamic control on the architecture of Martian magmatic plumbing, and is a possible probe of Martian tectonic history.

We have developed a model for discrete volcanic centers [2,3] based on the mechanism of "magmatic lensing," whereby pressurized magma chambers and volcanic loads can focus rising melt from a broad region around the volcanic center (Figure 1.a). This region may be quantified through the notion of a "capture radius" below the magma chamber, within which deviatoric stresses generated by the chamber are higher than the threshold stress needed to reorient a rising dike (taken to be 1 MPa [4]). This capture radius may be several times the chamber size at depth, and provides a natural length scale for the spacing between volcanic centers. With a Moho-level magma reservoir between 1 and 4 km in radius, this model predicts an average spacing between arc volcanoes on Earth that is generally consistent with that observed (~30-40 km) [2].

We apply the magmatic lensing model to Tharsis Montes by using a first-order (Mogi) solution for stresses around a spherical magma chamber beneath a free surface [5]. We neglect stress coupling between volcanic centers, and do not include the effect of individual volcano loads in the present study, assuming that the likely sizes of magma chambers (constrained by the caldera diameters of 40-100 km) are large enough to dominate volcanic loading stresses when scaled by gravity in many scenarios [2]. We do however evaluate the contribution of other important sources of background stress. In particular, we calculate the contribution of membrane stresses due to the Tharsis load [6], and True Polar Wander (TPW) stresses generated by the reorientation of the Martian spin axis in response to Tharsis formation [7]. These background stresses affect the capture radius of the volcanic center, estimated as half the straight-line distance between Tharsis Montes volcanoes.

By using the caldera sizes of Tharsis Montes volcanoes (20-50 km radius) as a proxy for typical magma chamber sizes, the simplest model of magma chamber lensing without background stress predicts the observed spacing (capture radius of 300-400 km) for magma chambers at a range of depths with overpressures between 10^8 – 10^9 Pa. These overpressure are above the generally accepted maximum overpressures for magma chambers on Earth. While a cold Martian geotherm may necessitate larger critical overpressures for eruption [4], and a viscoelastic treatment of this problem may reduce estimates of chamber overpressure, e.g., [8], we consider them to be unrealistic, and appeal to other contributing processes to account for the observed volcano spacing.

Background stress is a good candidate source of additional melt focusing. Tharis-loading deviatoric stresses are large (10^7 -10^8 Pa), and may be the cause of radial fractures around the province [6]. The wavelength of deformation is too broad (10s of degrees) to likely affect the discretization of individual Tharsis Montes volcanoes. However we note that as the Tharsis load is centered roughly on Pavonis Mons, gradients in compressive stresses induced in the elastic lithosphere should encourage a locus of melt transport around Tharsis Montes.

TPW stresses, on the other hand, are smaller (at least an order of magnitude) than the Tharsis loading stresses, and depend strongly on the magnitude of the reorientation as well as whether or not reorientation was complete at the time Tharsis Montes erupted [9]. In addition, there is interesting structure in these stresses near Tharis Montes (Figure 1.b). We find that TPW background stresses cause pronounced alignment of the capture radius, particularly for large reorientations (10-30 degrees, Figure 1.c-d). While there is some non-uniqueness in this problem, we find that there are scenarios in which combined magma chamber and TPW background deviatoric stresses achieve the observed capture radius, oriented along the present N38E alignment of the Tharsis Montes chain [9]. We speculate that Martian volcanoes may be used as paleo-stress indicators, and as constraints on TPW events and timing.

References: [1] Daniel Mege and Phillippe Masson. A plume tectonics model for the Tharsis province, Mars. *Planetary and Space Science*, 44(12):1499-1546,1996. [2] Leif Karlstrom, Josef Dufek, and Michael Manga. Organization of volcanic plumbing through magmatic lensing by magma chambers and volcanic loads. *Journal of Geophysical Research*, 114 (B10304). [3] Leif Karlstrom, Josef Dufek, and Michael Manga. Magma chamber stability in arc and continental crust. *Journal of Volcanology and Geothermal Research.* Doi:10.1016/j.jvolgeores.2009.10.003, 2009. [4] Allan M. Rubin. Propagation of magma-filled cracks. *Annual Reviews of Earth and Planetary Sciences*. 23:287-336, 1995. [5] K. Mogi. Relationships between the eruptions of various volcanoes and the deformations of the ground surfaces around them. *Bulletin of the Earthquake Research Instititute,* 36:99-134, 1958. [6] Donald L. Turcotte, R. J. Willemann, W. F. Haxby and John Norberry. Role of membrane stresses in the support of planetary topography. *Journal of Geophysical Research*, 86(B5):3951-3959, 1981. [7] Isamu Matsuyama and Francis Nimmo. Tectonic patterns on reoriented and despun planetary bodies. *Icarus,* 195:459-473, 2008. [8] A. V. Newman, T. H. Dixon, G. I. Ofoegbu and J. E. Dixon. Geodetic and seismic constraints on recent activity at Long Valley, California: Evidence for viscoelastic rheology. *Journal of Volcanology and Geothermal Research,* 105:183-206, 2001. [9] Stephanie C. Werner. The global Martian volcanic evolutionary history. *Icarus,* 201:44-68, 2009.

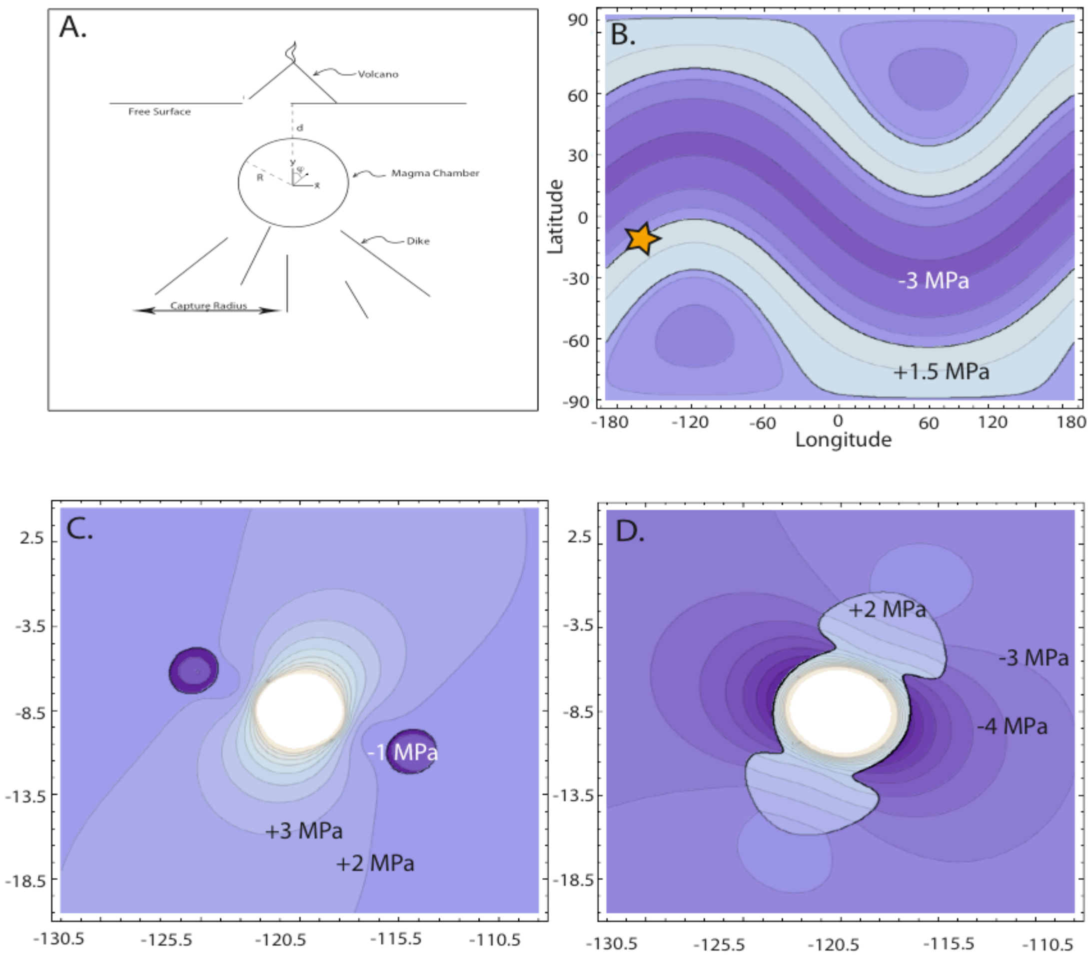

Figure 1. a) Schematic of the magmatic lensing mechanism. Modified from [2]. b) Global TPW greatest deviatoric principle stress field for a 30 degree reorientation, with Tharsis at -112 degree longitude. Contours in 0.5 MPa. Star is Arsia Mons, the center plotted in panels c) and d). c) Map view example of combined greatest principle deviatoric stress field below a magma chamber, for chamber stresses of the same sign as background TPW stresses. The elongation of chamber stresses would increases the NE spacing between centers in this case. Stress contours are 1 MPa. d) Same as c), but compressive chamber stresses are of opposite sign to background TPW stresses. In this case, the "capture radius" is still aligned to the NE but strongly suppressed.